Input to the NAS CTBT Study (9/9/09)

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Hafemeister CTBT Papers (2007-09)

1. How Much Reliability is Enough for a Comprehensive Nuclear Test Ban Treaty? *Physics and Society (Amer. Physicsal Society) 36(2),* 3-8 (April 2007).

2. Physics of Societal Issues: National Security, Environment and Energy (Springer, September 2007), Ch. 1-5.

3. Progress in CTBT Monitoring Since its 1999 Senate Defeat, *Science and Global Security 15(3),* 151-183 (December 2007).

4. The Comprehensive Test Ban Treaty: Effectively Verifiable, *Arms Control Today 38(8),* 6-12 (October 2008).

5. Capabilities of the IMS Seismic Auxiliary Network, *CTBTO International Scientific Study,* Vienna, June 10-12, 2009.

6. CTBT Space-Based Monitoring, *CTBTO International Scientific Study*, Vienna, June 10-12, 2009.

7. CTBT Evasion Scenarios: Possible or Probable?, *CTBTO Spectrum 13*, 22-25 (September 2009).

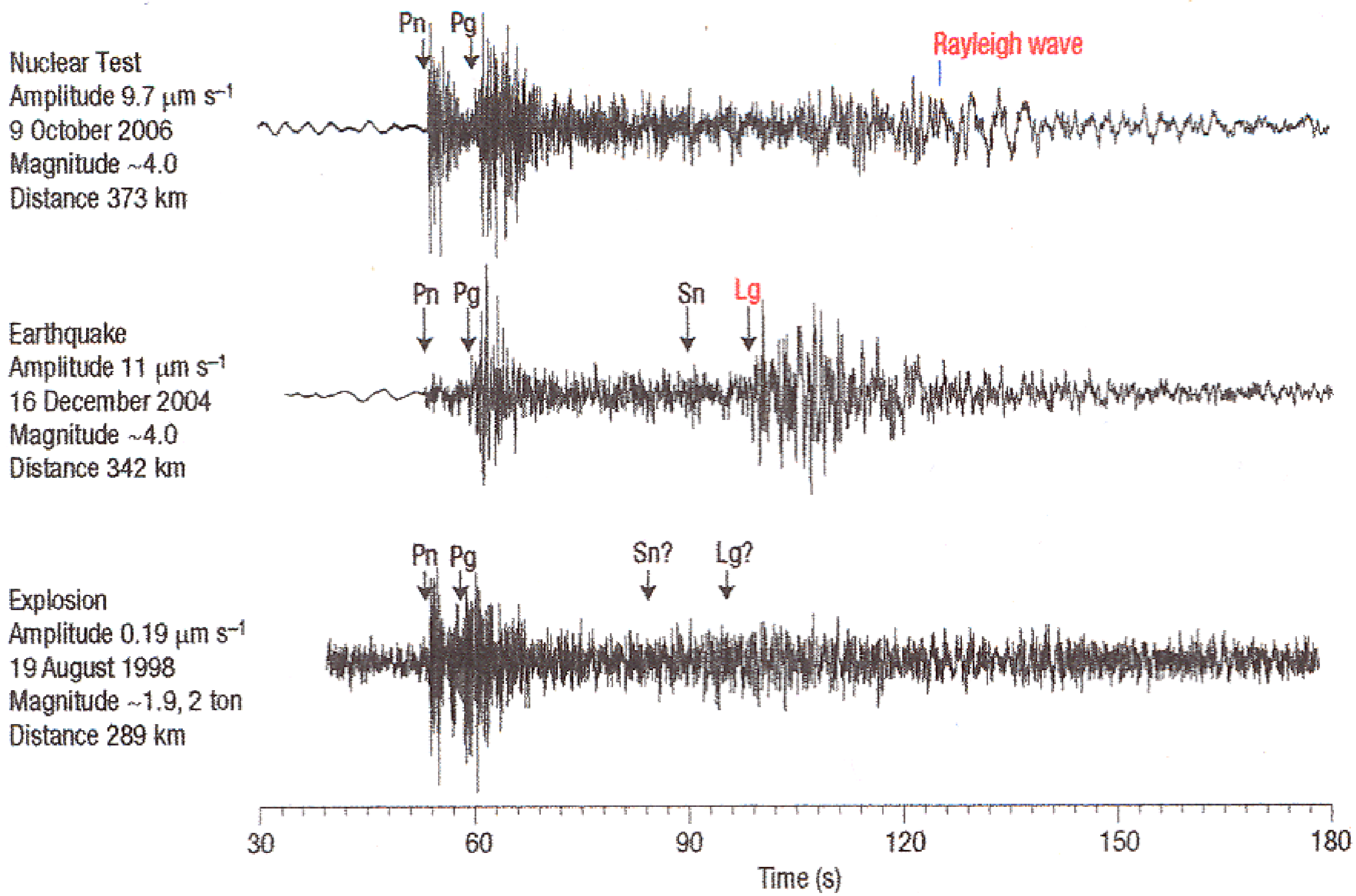
8. [with Thomas Graham, Jr.] Nuclear Testing and Proliferation – an Inextricable Connection, *Disarmament Diplomacy 91*, 9-19 (summer 2009).

9. Assessing the Merits of the CTBT, *Nonproliferation Review 16(3),* x-y (November 2009).

#1 Method	Description	IMS Assets (when complete)
Seismic	NAS concluded that explosions above 0.1 kton in hard rock can be detected in Asia, Europe, North America and North Africa. Tests in cavities can be detected above 1-2 kton for advanced nuclear weapon states, with risk of venting and excursion yields. This limit is perhaps 0.1 kt for new nuclear nations.	IMS will use 50 primary and 120 auxiliary seismic stations. Arrays of seismographs and regional seismographs can obtain lower threshold yields. In addition, thousands of non-IMS stations have data that could trigger an on-site inspection.
Hydroacoustic	NAS concluded that explosions above a few kilograms can be detected in Southern Hemisphere, and above 1 ton for all oceans.	IMS will use six hydrophone arrays and five T-phase monitoring stations.
Infrasound	NAS concluded that explosions above 1 kton in the atmosphere can be detected, and above 0.5 kton over continents.	IMS will use 60 infrasound monitoring stations.
Radionuclide	NAS concludes that explosions above 0.1–1 kton can be detected to identify the event as a nuclear explosion. The 0.6 kton North Korean test was detected at 7,000 km distance.	IMS will use 80 particulate monitoring stations, and 40 of these will also detect radioxenon. NTM sensors can also be placed on airplanes for close approaches to suspected test sites.
InSAR (Interferometric Synthetic Aperture Radar)	InSAR can measure subsidence as low as 0.2-0.5 cm in many locations, with yields above 1 kton at 500 m depth. InSAR can determine locations to 100 meters.	United States has four classified SAR satellites. Europe, Canada and Japan sell unclassified SAR data for as low as $1,000 each.
On-Site Inspections	Any CTBT party can request an OSI, which needs 30 of 51 votes in the Executive Council.	Photos and radioactivity obtained by air and ground. Mini seismic arrays can observe aftershocks. Magnetic anomalies, SAR, soil data obtained with GPS locations.
Confidence-Building Measures	After CTBT enters into force, nuclear weapon states could locate more sensors at test sites to lower thresholds further.	Close-in sensors could detect seismic, infrasound, electromagnetic pulse, radionuclide and other data indicative of a test.
National Technical Means	U.S. NTM technologies have considerable reach and precision.	NTM sensors are located in space, in the atmosphere, on the ground, in the oceans and underground.

600 t

2 t

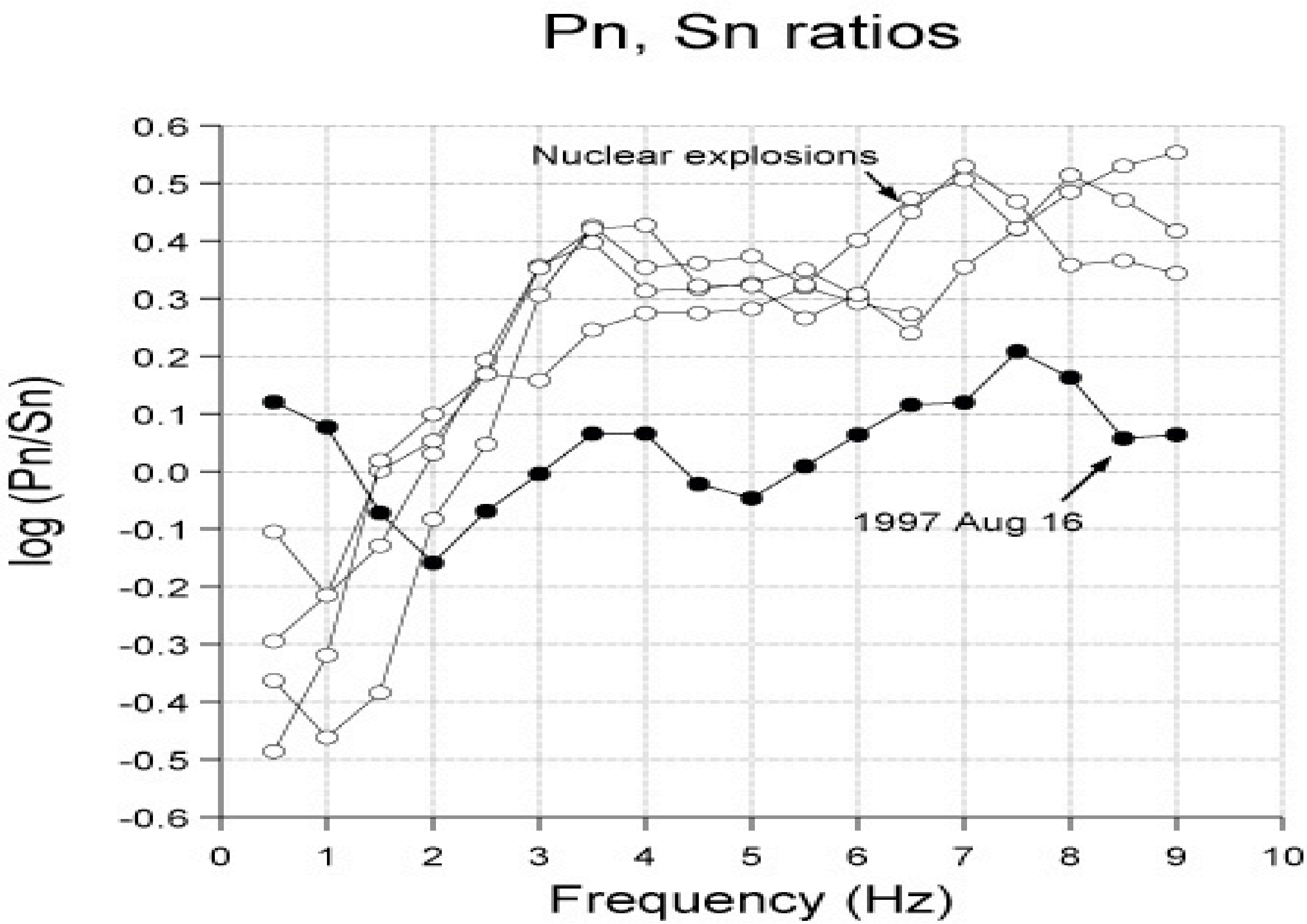


Regional Seismic: DPRK, 9 Oct. 2006 (0.6kton)

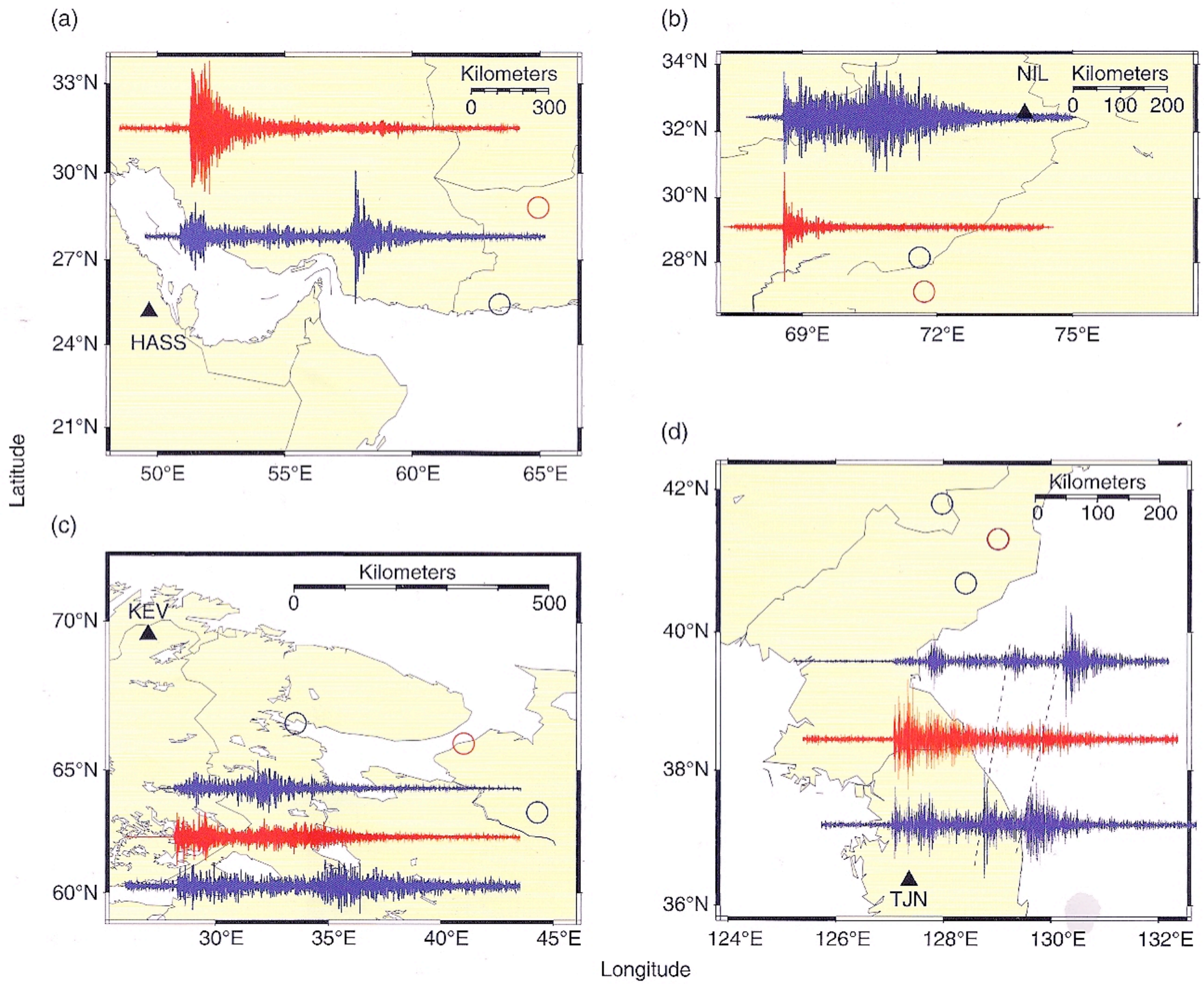
22 IMS stations (60% complete)

[May 2009, 2.5 kt, 61 IMS (70% = 120/170)]

m_b = 4.0, 4.0, 1.9 (0.002 kt) => limit 0.002 kt, Richards/Kim



NZ Explosions, greater P/S ratio above 3 Hz



LLNL (S&TR, 3.09): 6-8 Hz, QUAKE–TEST

(a) Pakistan(1500 km), (b) India(500 km), (c) USSR(600 km), (d) N Korea(500 km)

Status of IMS Monitoring Stations (9/2009)

	total	planning	under const	testing	certified
primary seismic	50	3	3	6	38
auxiliary seismic	120	6	12	19	83
hydroacoustic	11	0	1	0	10
infrasound	60	12	7	2	39
radionuclide	80	7	12	7	54
noble gases	(40)	(20)			(20)
radnuc labs	16	6	0	0	10
TOTAL	**337**	**33**	**29**	**26**	**249**
		10%	**9%**	**8%**	**74%**

Total of certified + testing + under construction

Total = 249 + 26 + 29 = 304/337 = 90.2%

Cooperative Measures

-- Not a condition of ratification, but bilaterally over time, step by step, by agreement or reciprocal unilateral, as trust increases.

-- OUO reports from LANL and LLNL

-- My initial suggestions are:

at the edge of the test sites:

-- passive seismic

-- radioxenon and particulate monitoring

-- infrasound

Technologies

- analog to digital seismographs
- narrow-band to broad-band seismographs
- 1-axis to 3-axis to arrays
- increased density of seismic stations
- correlation detection
- teleseismic to close-in regional
- other technologies assist seismology

Analysis

- magnitude picks to correlated templates for similar paths
- improved earth models, improved algorithms
- discriminate sources in frequency bands above 5 Hz
- geological bias, preferential absorption

Monitoring Progress

Arrays detect and identify events to a threshold of **2–2.5 m_b** from over 2000 km away, corresponding to explosive yields less than 0.01 kt for tamped explosions and less than 1 kt for an explosion decoupled in a large cavity.

Monitoring with **regional waves** P_n, L_g and coda regional waves is very encouraging. Using **old Soviet data 500–1500 km** from Semipalatinsk Test Site, seismic signals were located for **all but two tests over one ton**. Regional spectra contain more information than the narrowband magnitudes.

If the 120 IMS **auxiliary** stations are operated in **near-real-time***,* the thresholds can be lowered by 0.25–0.5 m_b.

All primary stations could **become array** stations.

Data from the **87 Global Seismic Network** stations not in auxiliary network could be co-listed in the IMS event bulletins. Many other international stations are available.

New algorithms for **regional seismology and seismic models** enhance abilities to discriminate between event sources below 3.5 m_b.

Correlation detection can lower threshold by 0.5–1.0 m_b for arrays and triple axis networks. Extremely useful for former test sites and is being extended to earthquakes, such as 1997 Kara Sea event.

Cross-correlation of **seismic waveforms** can reduce location uncertainties by 10–100 from those initial–wave times in seismic–active regions or in former test sites.

InSAR measures subsidence after nuclear tests with an accuracy of a few mm and location accuracy of less than 100 m. **Threshold for InSAR** to locate nuclear tests **is less than 1 kt** if SAR data was taken prior to the nuclear test. If prior SAR data does not exist, then the threshold is higher, perhaps 20 kt. InSAR also detects test–site activity.

Cooperative measures near test sites can detect yields of less than **10 kg (equivalent)** by using passive–seismic, infrasound, EMP, and video sensors. Dosimeters next to experiments can **detect milligram** fission and fusion yields.

See Kvaerna and Ringdal (ISS-Seismo-15) **quantify and rank** primary and auxiliary IMS stations.

#2: Decoupled Tests in Cavities

Must accurately predict yield to avoid ***yield excursions***. Average yield of seven first tests is 22 kt (9–65 kt), then DPRK at 0.6 kt. It is difficult for new nuclear nations to obtain a specific yield of, for example, 0.1 or 1.0 kt

Need to ***hide removed materials*** from satellites.

Surface subsidence after nuclear test of few mm is observable with InSAR with 100–m location accuracy. Indian and Pakistani tests easily located with optical SPOT images with 5–m resolution

Radionuclide venting is a serious risk. The Soviet Union did not contain 90% of the underground tests at NZTS from 1964 to 1988 (40% for all underground Soviet tests). **US had significant releases as late as 1986**. Venting very serious risk for beginning nuclear states. See "Radiological Effluents Released from U.S. Continental Tests (1961-92), DOE/NV UC-702.

Regional waves at higher frequencies with lowered decoupling factor.

Series of tests needed to develop significant weapons.

NTM data may be used by the CTBT Executive Council.

NAS 2002): fully–decoupled explosion larger than 1–2 kt cannot be confidently hidden in a cavity, particularly for a new nuclear state

$$\mathbf{P_{success} = \Pi_i\ P_i} = (P_{venting})(P_{yield\text{-}exccursion})(P_{hide\text{-}materials})(P_{subsidence}) \times (P_{regional\text{-}seismic})(P_{test\text{-}series})(P_{NTM})$$

- **High confidence 90%** for each step gives $P_{success} = (0.9)^7 =$ **48%**
- 4 failure paths, $P_{success} =$ **66%**
- **Yield prediction and venting** at medium confidence,

  $P_{success} = (0.9)^5(0.5)^2 =$ **15%**

- ***National Intelligence Estimate*** and related papers didn't addresses this.

Evasion Scenarios, Possibilities vs. Probabilities

1. Difficult to make a NNWS warhead to 1.0 kt, or 0.1 kt
2. Difficulty to Instrument the covert test
3. Military Significance of Violation
4. Nitze-Baker definition of Effective Verification
5. Net Benefit Analysis of the Treaty (importance of gains and losses if cheating happens)
6. Other assets, auxiliary, arrays, NTM, venting, significant yield excursions,
7. Detection level clearly below 3.5, which is arbitrary.
8. Identification level of good signals is about same as detection level.
9. Don't use NTS conversion for remainder of the Earth.

#3: IMS Seismic Auxiliary Network (Hafemeister, ICC-Sesimo-12)

number of stations **(Prim. + Aux.)/Prim = 170/50 = 3.4.**

access ratio: $\mathbf{r_{PA}/r_P = 1/(3.4)^{1/2} = 1/1.84 = 0.54 = 0.5.}$

Cautious assumption, **L_g amplitude falls as the inverse of the square root of the distance ($1/r^{0.5}$)** from the source. **This ignores faster fall-off of more important P_g wave amplitude that falls as the inverse of the distance (1/r). Also ignore the frequency dependent attenuation factor, Q(f), which reduces the amplitude of the very relevant higher frequency waves.**

The total seismic power P_{seismic} over a cylindrical area of depth H and circumference $2\pi r$, gives average seismic power flux of

$$p_{\text{seismic}} = P_{\text{seismic}}/H2\pi r.$$

Seismic power is proportional to the yield of the explosion Y, giving seismic power flux proportional to yield over distance.

$$p_{\text{seismic}} \propto Y/r.$$

The more distant P seismograph is sensitive to a threshold amplitude (A_T) from a threshold yield Y_T at a distance r_T

$$\boldsymbol{A_{\mathrm{T}}} = \mathbf{c}\,(\mathbf{Y_T}/\boldsymbol{r}_{\mathbf{T}})^{1/2},$$

where c is a constant.

Seismic magnitude is $\boldsymbol{m} = \mathbf{a}\log(\boldsymbol{Y}) + \mathbf{b},$

Reduction in threshold magnitudes from the P network to the PAux network is

$$\Delta m_{\mathrm{T}} = m_{\mathrm{T}P} - m_{\mathrm{TPAux}} = [\mathrm{a}\log(\mathrm{Y_{TP}}) + \mathrm{b}] - [\mathrm{a}\log(\mathrm{Y_{TPAux}}) + \mathrm{b}]$$

$$= \mathrm{a}\log(\mathrm{Y_{TP}}/\mathrm{Y_{TPAux}}) = \mathrm{a}\log(2) = (0.8)\,(0.30) = 0.25.$$

Result for P_{Lg} waves would be $\Delta m_T = 0.5$. Other factors must be considered, but clearly the auxiliary network makes a valuable, understated, contribution.

#4: Effective Verification

"....if the other side **moves beyond the limits** of the treaty in any **militarily significant** way, we would be able to detect such violation in **time to respond** effectively and thereby **deny the other side** the benefit of the violation." [**Paul Nitze**, INF Ratification 1988]

"Additionally, the verification regime should enable us to detect **patterns of marginal violations** that do not present immediate risk to the US security." [**James Baker**, START Ratification 1992]

How Much Verification Is Enough?

Detect one of n covert tests. $P_n = 1 - (1 - P_1)^n$.

3–test detection	1 test	3 tests
high confidence	$P_h = 0.9$	$P_3 = 0.999$
medium confidence	$P_m = 0.5$	$P_3 = 0.88$
low confidence	$P_l = 0.1$	$P_3 = 0.27$

Analysis should include:

-- multiple tests

-- auxiliary net (- 0.25-0.5 m_b) plus NTM, GSN, etc.

-- NTM

-- a cheater wants 90% success rate gives a 10% detect/identification rate. A 10% D/I rate lowers the threshold yield by about 0.5 m_b with respect to a 90% D/I rate. [O. Dahlman, et al, Nuclear Test Ban, p. 167.]

2200 Warheads in 2012

1400: 14 Tridents (12x120 *operational*, 2x120 in maintenance)
450: 450 Minuteman III
≈300: 56 B52, 21 B2 heavy bombers

Reserve forces (2500): Trident overhaul (200), response force [1000 upload aircraft, 350 bombs under US/NATO control, 300 SLCMs].

Russia projected to have 1500 operational warheads after 2012.

400 on Topol-M (SS–27, 10/year which, carry 1–4 warheads?) Slow progress on 2 Borey–class submarines with Bulava SLBMs and on aviation forces, both these legs could carry 500–700 warheads. Russia could destroy:

Destroy		**Survive**
300:	all heavy bombers off alert	0
500–700:	33–50% SLBMs	700–1000
350:	80% of US ICBMs	100
1150-1350	**Total**	**800-1100 + tacticals + reserves**

Worse-case analysis applied to START I and II by SFRC.

#5. Interferometric Synthetic Aperature (InSAR)

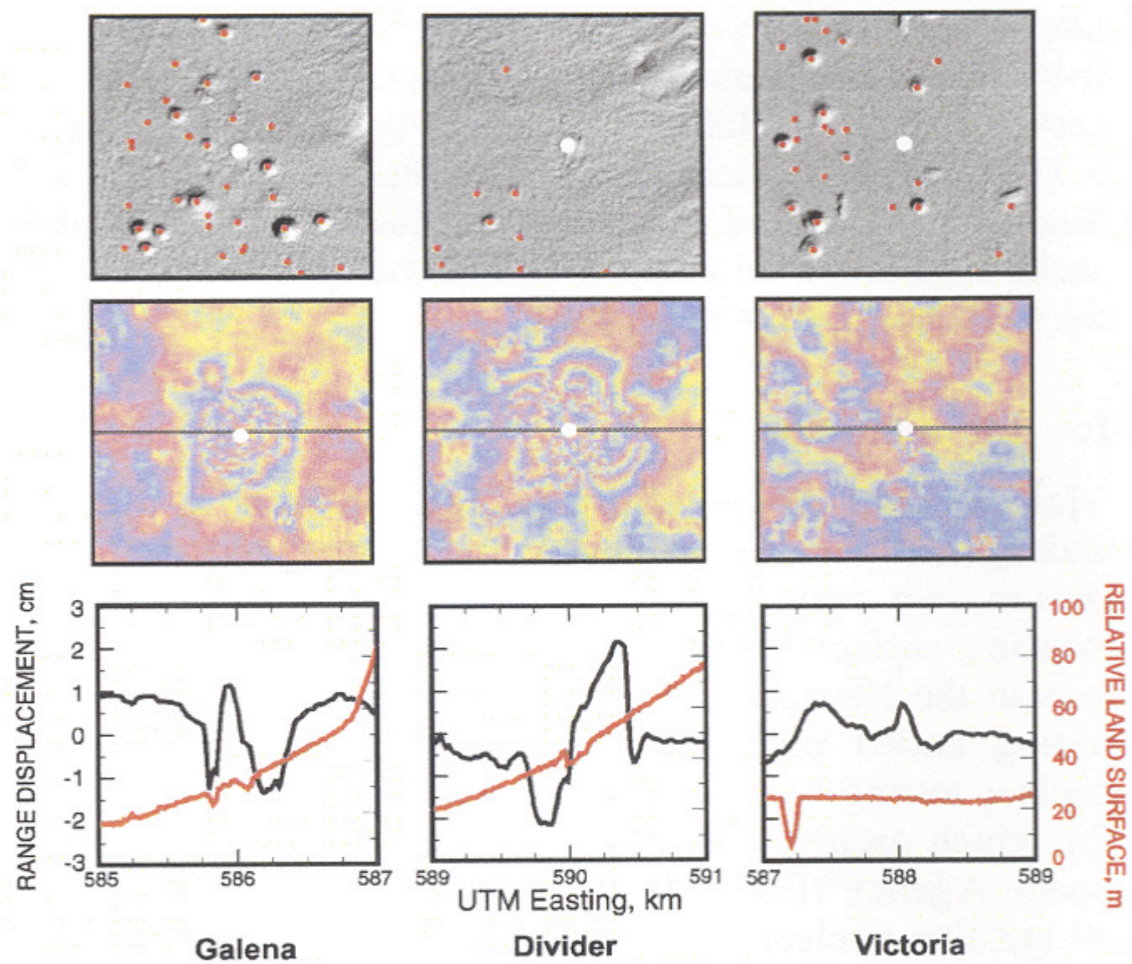
OSI Location: InSAR can locate to 100 m = 0.1 km, an area of 0.01 km^2, which is 10^{-5} of the OSI limited area of 1,000 km^2.

InSAR should examine the “deep-thick” salt deposits.

If a favorable location, InSAR can detect and locate 1 kt tests at the depth of 500; NTS very good, Lop Nor less so.

InSAR can discriminate between explosions and earthquakes.

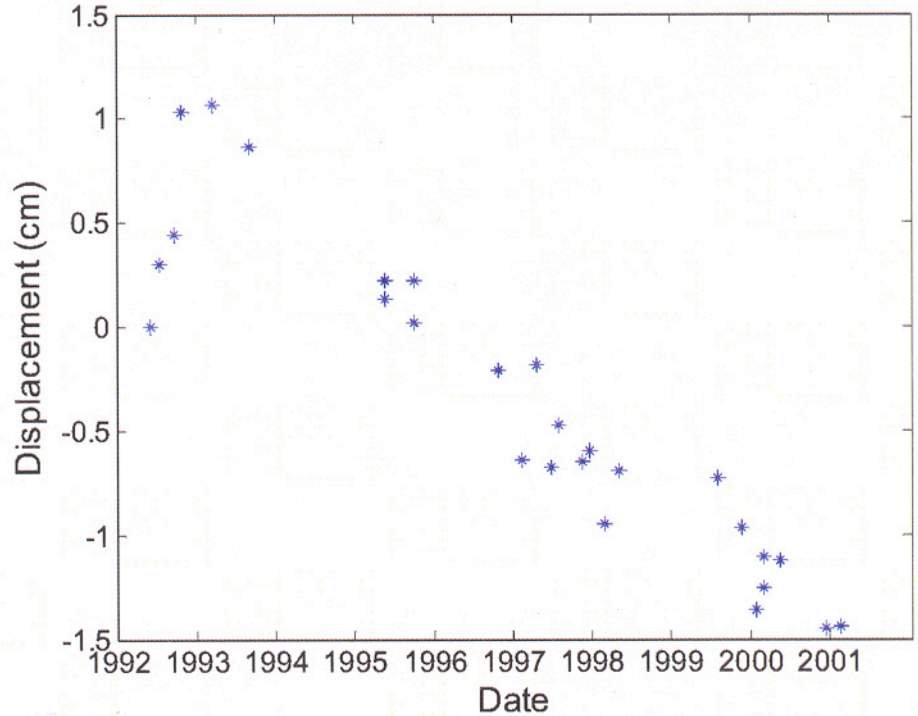
InSAR software and commercial digital data is not expensive, and readily available, as a common university research skill.



InSAR: M_L = 3.9, 4.4, 2.7 at 340, 401, 244 m

Chemical Ex. (NPE): 1.4 kt, 405 m, 4.1 ML_L

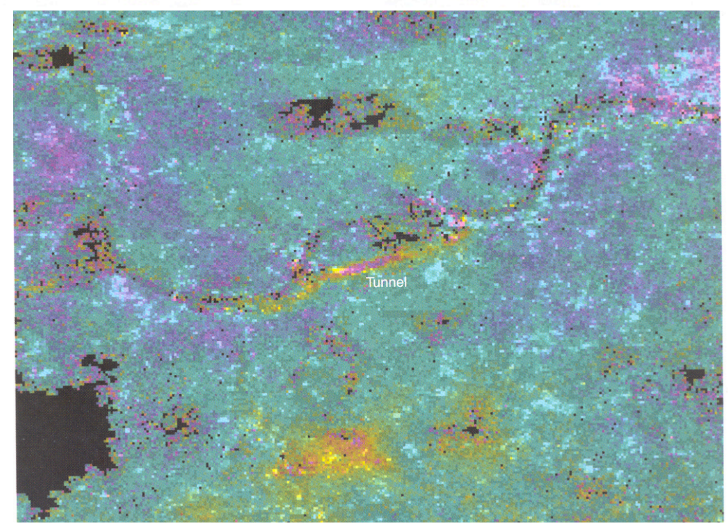
P. Vincent, *GRL* 30(22), 2141 (2003)



London Jubilee line, 20 m

1992–2001, 2.5 cm linear

error less than 2 mm



#6. Radionuclide Monitoring

IMS stations improve by a factor in 10 years.

Atmospheric tests easily detected

Underground tests have leaded in the past (slide 10)

Air or closer ground sensors can enhance flux by more than a million (nearer and sooner; ie., DPRK-1). A publicized US aircraft capability can deter tests. This should be public and not classified.

Medical Mo^{99} production facilities increase background much more than reactors. What is the cost to capture and temporarily hold Xe at these few sites?

#7: Warhead Reliability, Safety and Missions

1. Safety is not a primary issue.
2. Successful Life Extension Program, W76, W87
3. Los Alamos reestablishes ability to make new pits, W88
4. NNSA (reviewed by JASON) determines that pits will not have aging effects for at least 85-100 years (with Pu-238). Ageing problems are with the non-nuclear components which can be tested. In the past, tested rarely for reliability.
5. More robust tritium transfer system devised.
6. Margins to Uncertainties (M/U) improves as margins have been increased and uncertainties reduced
7. 3-d calculations, DAHRT and NIF

•One US nuclear weapon accident since 1968, the 1980 liquid-fueled Titan in a silo in Arkansas. No radioactivity was spread.

•Two accidents spread considerable radioactivity, both airplane accidents at Palomares, Spain (1966) and Thule, Greenland (1968). Practically all (29 of 32) nuclear weapon accidents resulted from aircraft accidents.

•No longer use liquid-fueled missiles, SRAMs or unsafe battle field weapons. Now fly/store bombers without nuclear weapons, removing most of the problem.

• Cost to mitigate to save a life by adding fire resistant pits and insensitive high explosive for ICBM/SLBMs too expensive (DoD of both parties).

Kill probability of hard-target warheads as a function of n warheads (no fratricide).

$P_{k1} = R \times SSKP(Y, H, CEP)$

Let SSKP = 1, then $P_{k1} = R$

$P_{kn} = 1 - (1 - P_{\mathrm{k1}})^n = 1 - (1 - \mathrm{R})^n$

For R=0.5; $P_{k1} = 0.5$, $P_{k2} = 0.75$, $P_{k3} = 0.88$

For R=0.25; $P_{k1} = 0.25$, $P_{k2} = 0.44$, $P_{k3} = 0.58$

Large reductions of 50% and 75% are of concern only for the case of a pre-emptive attack on a large nuclear force, where all the enduring warheads would be used and couldn't be exchanged.

50% Yield Reductions:

H=2000 psi, R=0.9, CEP = 0.05 nmi = 100 m

50% yields: Y(W88)=455 kt, Y(W76) = 100 kt,

	455 kt	228 kt	100 kt	50 kt
P1	0.90	0.88	0.80	0.67
P2	0.9895	0.9849	0.957	0.888
P3	0.9989	0.9981	0.991	0.963

#8. NPT-CTBT Connection.

The 19 April 1995 Letter to the 1995 NPT-Review and Extension Conference by France, Russia, UK and US (China agreed later) stated a determination to complete the CTBT with a request to the NNWSs that the NPT provisions be made permanent (the quid pro quo):

> *We reaffirm our determination to continue to negotiate intensively, as a high priority, a universal and multilaterally and effectively verifiable comprehensive nuclear test–ban treaty, and we pledge our support for its conclusion without delay.*
>
> *We call upon all States parties to the [NPT] Treaty to make the treaty provisions permanent. This will be crucial for the full realization of the goals set out in Article VI.*

1995 Statement Accompanying the renewal of the NPT without a time limit. This was the one big chance for NNWS states to have leverage on the NWS states.

"The completion by the Conference on Disarmament of the negotiations on a universal and internationally and effectively verifiable Comprehensive Nuclear-Test Bay Treaty no later than 1996. Pending the entry into force of a Comprehensive test Ban Treaty, the nuclear weapon states should exercise utmost restraint."

UN General Assembly CTBT Laudatory Votes

2003: 173 - 1 - 3

2004: 177 - 2 - 3

2005: 172 - 1 - 3

2006: 172 - 2 - 3

2007: 176 - 1 - 3

2008: 175 - 1 - 3

Total: 1045 - 8 (6US, DPRK, Palau) -

18 (6India, 6Mauritius, 6Syria)

Colombia ratifies in 2008, -5 abstentions